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# INUNDATION CAUSED BY SWELLS AND LONG-PERIOD WAVES PENETRATING FROM RIVER MOUTH AND ITS COUNTERMEASURES - A CASE STUDY AT THE SEGAMI RIVER, IBARAKI PREFECTURE, JAPAN

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## SYNOPSIS

Inundations process caused by the penetration of swells and long-period waves into the Segami River mouth in Ibaraki Prefecture was investigated by means of field observation and numerical analysis. Due to the river improvement for the inundation caused by rainfall, the riverbed was deepened. As a result, in this case, the wave penetration from the sea has increased and inundation caused by waves has emerged. The effectiveness of the countermeasure plans (constructing an inner breakwater off the river mouth and a reduction pond in the river) against inundation was confirmed by the numerical analysis.

## INTRODUCTION

The Segami River, a class B river under the management of Ibaraki Prefectural Government, flows through a densely inhabited area near the Kujihama railway station, Hitachi City, Ibaraki Prefecture, and reaches Hitachi Port on the Pacific coast. The drainage area of this river is 1.59km$^2$, its design flood discharge is 28m$^3$/s (at Nagisa Bridge), and its length of the watercourse is 750m (the section of class B river). Due to the narrow river channel and the low elevation of the land, the inhabitants have frequently suffered from inside water inundation disasters. On October 18, 1979, a rainfall of the maximum hourly intensity of 27 mm inundated about 200 houses, with a maximum depth of flooding of 0.8 m recorded near the station. River improvement works including a channel widening and a riverbed excavation, which conducted from 1972 to 1994, helped to prevent flooding. However, additional new problems inundation caused by run-up waves coming from the sea have emerged: swells running upstream through the riverbed frequently have inundated at a box culvert about 700 m from the river mouth and have caused flood damages to nearby houses.

Studies on inundation damages due to swells penetrating from the mouth of small-scale rivers and countermeasures against them have been scarce. Uda and Noguchi (1) reported that a funnel-like topography of the mouth of the Okajiri River, Kyoto Prefecture, caused amplification of run-up height due to an abrupt decrease of riverbed cross-sectional area. They suggested that such an upstream penetration of waves could be prevented both by constructing an artificial sand bar at the river mouth, thus decreasing the width of river at low-water level, and by forcing the flow to meander in the narrowed low-flow channel. Our present study also aims to examine the phenomenon of run-up swells and the effectiveness of flood countermeasures in the Segami River area.

## TOPOGRAPHY AND GENERAL FEATURES OF THE SEGAMI RIVER

The Segami River was once a tributary of the Kuji River, but was separated from it by river improvement works when Hitachi Port was constructed. Figure 1 shows an earlier topographical chart (1960 edition) before the improvement works of the Kuji River, and Photograph 1 is an aerial view around the river mouth area, taken on December 22, 1999, after the river improvement works had been completed.

Before the construction of Hitachi Port, the area around Kujihama Station was lowland surrounded by hills and faced the left bank of the Kuji River meandering toward the north at this point. As shown in Photograph 1, the present topography of the Segami River is divided into two parts by Segami-Shinbashi Bridge. Upstream of this bridge is the earlier riverbed of the Kuji River and flows into a inhabited area, and its downstream part flows into a scarcely inhabited area which was reclaimed for construction by the Hitachi Port authorities. The Segami River opens into Third Anchorage of Hitachi Port. Its river mouth is narrow and faces southward due to a breakwater, and an inner breakwater has been constructed recently.

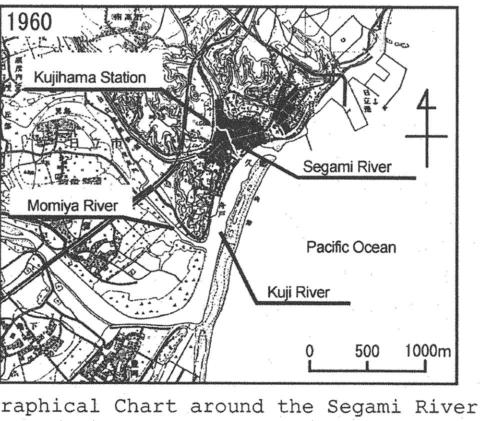
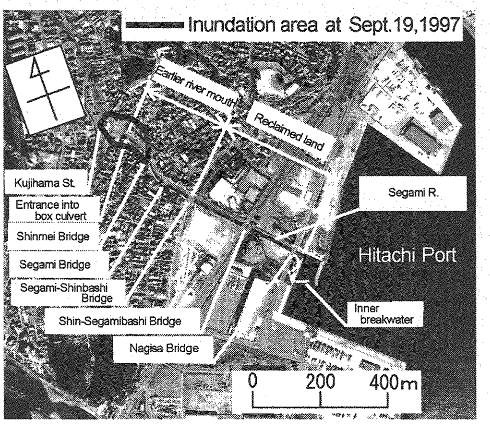



Figure 1 Earlier Topographical Chart around the Segami River Mouth (1996 Edition)

The Segami River mouth is vulnerable to the penetration of waves from the Pacific Ocean, because it faces in the main direction of incident waves reaching Hitachi Port. Short period waves may be prevented from entering the river by constructing breakwaters, but longer period waves penetrate the anchorage and run up the river, causing flood damages. Photograph 1 shows a flooded area on September 19, 1997, and Figure 2 shows the depth of flooding at this time.




Photograph 1 Aerial View of the Present Segami River Month taken on November, 1999

Figure 2 also shows a longitudinal section along the Segami River channel. While elevation of the area around Kujihama Station is 1.1m above M.S.L. at the lowest, the reclaimed land nearer the river mouth is as high as 2.2m to 2.9m above M.S.L.. Consequently, the longitudinal section of the river forms a shallow U-shape with the lowest point being near Kujihama Station, which makes the area vulnerable to accumulations of rain water. On the other hand, a gentle bed slope of the river near Kujihama Station, about 1/900, as compared with 1/300 in the reclaimed land, makes it difficult to dump run-up waves from the sea. The crown height of revetment, with nearly the same elevation as the surrounding area, ranges from 2.35m above M.S.L. at the river mouth to 1.37m above M.S.L. near Kujihama Station. The design high-water level at this place is 0.77m above M.S.L. leaving 0.6m of freeboard to the revetment crown. However, as the underside of upper slab of the box culvert at this site is 0.45m lower than the crown height of revetment, there remains only 0.15m of freeboard until the box culvert is filled when the design high-water level is reached.

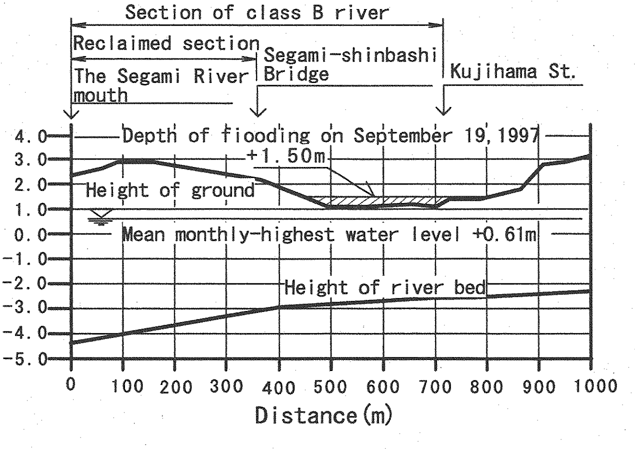



Figure 2 Longitudinal Section of the Segami River

The only outlet of the Segami River, without any branch, opens into the anchorage. The river mouth, about 4m deep and 7m wide, is connected to the anchorage of about 5m in depth. Between the mouth and the box culvert about 700m upstream, the river is an open channel armored with concrete. The channel at about 400m from the mouth has a compound cross-section of 7m width, and further upstream, it is single sectional with decreasing width and depth, reaching a width of about 3.5m and a depth of about 3m at the box culvert. Thus, the channel narrows by 50% and shallows by 30% during the course from the mouth to the place vulnerable to inundation.

## METEOROLOGICAL AND OCEANOGRAPHICAL CONDITIONS DURING THE PERIOD OF INUNDATION IN THE SEGAMI RIVER AREA AND PHOTOGRAPHS OF THE INUNDATION

On five occasions when inundation damages occurred in the Segami River, meteorological and oceanographical data were examined: tide level (at Hitachi Port), significant wave height and period (at nearby Hitachi-Naka Port: Located to the south of 9 km of the Hitachi port.), and atmospheric pressure and rainfall depth (at Hitachi-Naka Port, or at Hitachi Port if data not available in the former). All of the inundation damages occurred in autumn: 4 cases in September and 1 in October. In four of the cases damages were caused by typhoons and in one case by an atmospheric depression. Figure 3 shows changes of tide level, significant wave height and period, atmospheric pressure and rainfall depth on the days when inundation occurred.

Meteorological and oceanographical conditions of the inundations are summarized as follows:

(a) September 17, 1995 (Before construction of the inner breakwater)

As Typhoon No. 12 approached, atmospheric pressure decreased to 987.5hPa. An extreme diurnal inequality occurred and a tide level of over 0.6m above M.S.L. was observed during 8h to 23h. When the observed and estimated tidal levels at Hitachi Port were compared with each other on the same day, departure from the normal tide reached about +0.6m. The significant wave height was 4.1m at 14h, and the wave period gradually increased and reached about 12s at 20h.

(b) September 1, 1996 (Before construction of the inner breakwater)

Atmospheric pressure gradually decreased as Typhoon No.14 approached. Rainfall was hardly observed. Little diurnal inequality occurred, with a departure of +0.15m from the normal tidal level. But waves of a maximum significant height of nearly 3m and of period of 12s penetrated into the port.

(c) September 22, 1996 (Before construction of the inner breakwater)

Atmospheric pressure abruptly decreased to 981.8hPa at 17h as Typhoon No. 17 approached, and a rainfall of hourly precipitation of 21mm was recorded on 14h on September 22. A conspicuous diurnal inequality occurred, and a tidal level of more than 0.6m was observed between 11h of the day 22 and 2h of the day 23, with a maximum departure from the normal tide reaching about +0.5m. The significant wave height was also 7m at 18h, and the period varied between 8s and 12s.

(d) September 19, 1997 (After construction of the inner breakwater)

As Typhoon No. 20 approached, the atmospheric pressure went down to 994.3hPa at 13h. A slight rainfall of 13mm in total was observed. Departure from the normal tide level became greater in accordance with lowering atmospheric pressure, reaching about +0.5m form 11h to 16h. Waves of significant height of 4m and of long period of over 12s penetrated the port.

(e) October 27, 1999 (After construction of the inner breakwater)

From October 26 to 28, a rapidly developing low pressure passed from East China Sea through the Pacific coast of Japan, bringing about record rainfalls in many parts of the country. At Hitachi Port, a heavy rain of the maximum hourly precipitation of 81.5mm was recorded at 21h of October 27. As the low pressure approached, an increasing departure from the normal tide level of over +0.3m sustained from 18h of the day 27 to 6h of the day 28. The significant wave height increased from 12h, reaching about 5m at 22h of the day 27, but the period was less than 10s.

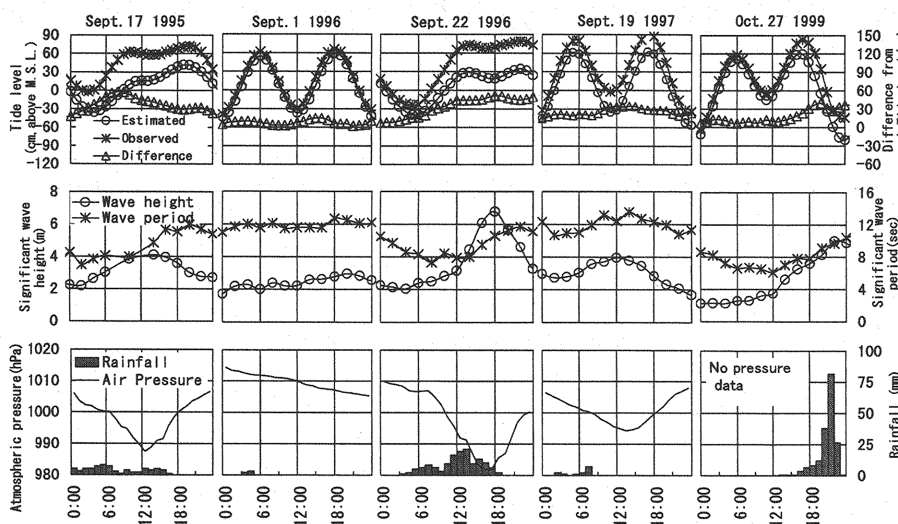



Figure 3 Meteorological and Oceanographical Conditions on the Days of Inundation
Upper : Tide level and difference from normal tide
Middle: Height and period of significant waves
Lower : Atmospheric pressure and rainfall

In all of the 5 cases above, inundation occurred along with a typhoon or as a strong low pressure approached. Departure from the normal tide level was high, ranging between +0.3m and +0.6m except for one case. Significant wave height was also high, exceeding 4m (period being 11s to 13s) except for one case. Inundation occurred even when there was little rainfall. In the case of September 1, 1996, where inundation happened without any of these specific conditions recorded, the only event that could be related to inundation was the sustained duration of waves of about 12s-period. As will be discussed later, swells which may cause inundation after entering Hitachi Port have a comparatively long period (Wave characteristics of Hitachi Port were converted from the wave data at Hitachi-Naka Port). For example, over 50% of the waves higher than 4m at the port mouth had a period longer than 12s. In 46% of incidents the direction of waves was E, and in 35.8% the direction was ESE. The prevailing energy direction of high waves was E 7.4° S.

Figure 4 shows a monthly mean sea level at Kuji Fishing Port which is located north of Hitachi Port. The monthly mean sea level is at the lowest in March, -0.12m against the yearly mean sea level (0m), and is at the highest in September, at +0.11m. On September 1997, the highest sea level of +0.15m was recorded. These findings suggest that the high sea level in autumn tends to increase the probability of inundations.

Figure 5 shows a tidal observation record at Kuji Fishing Port, 2h to 20h, on September 19, 1997. Alongside of the tidal level variation, a secondary undulation of tide with an amplitude of about 0.7m can be observed. By means of a spectral analysis, in which observed readings at 75s intervals were analyzed by the spline interpolation at 10s intervals, a peak period around at 150s was detected. This long-period of oscillation (secondary undulation of tide) may have been caused by a harbor resonance of long-period waves coming from the ocean.

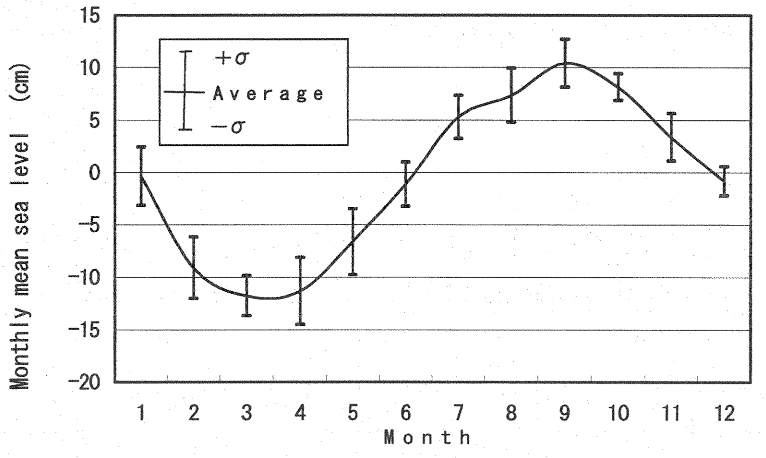



Figure 4 Seasonal Change of Mean Sea Level at Kuji Fishing Port (Yearly Mean 1996~1999)

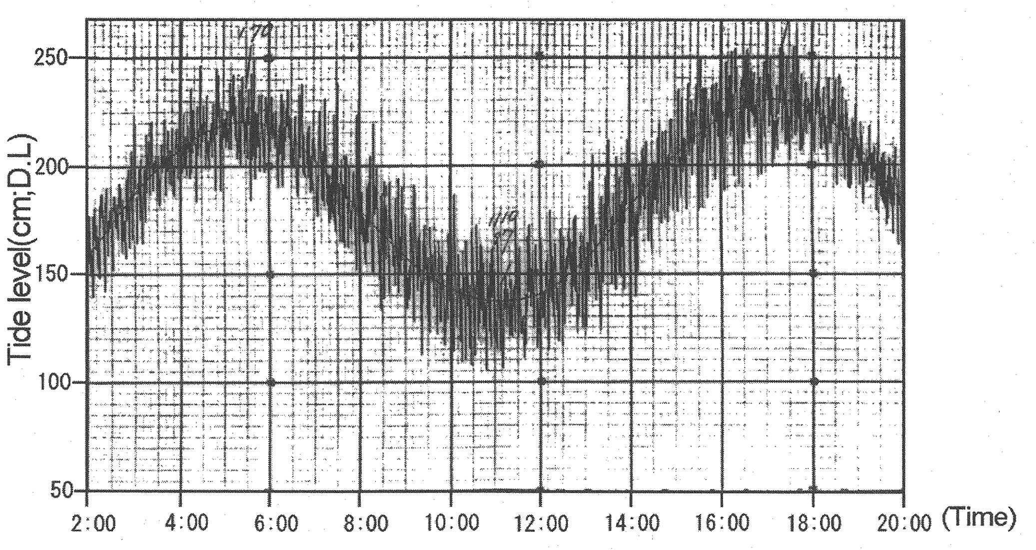
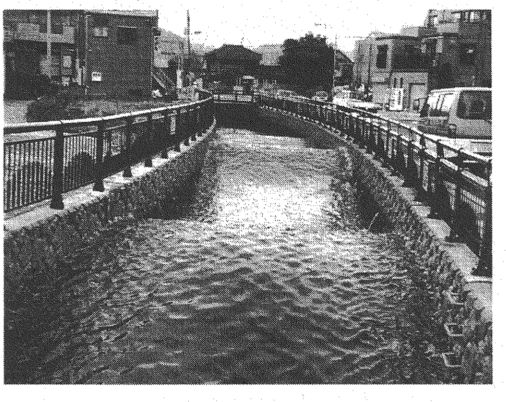


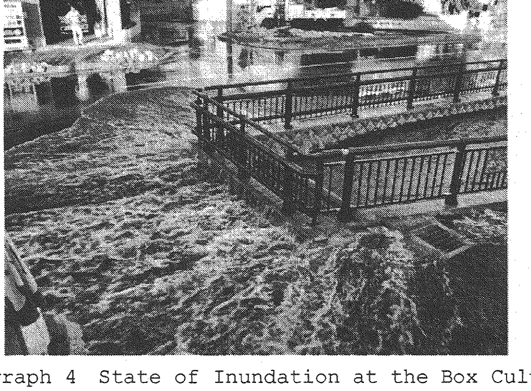

Figure 5 Secondary Undulation of Tide Level in Tidal Observation Record.
(2h to 20h on September 19, 1997)

When Typhoon No. 20 occurred on September 19, 1997, run-up waves from the river mouth caused overflowing from the crown of revetment near the Kujihama railway station and extensive flood damages in the area. The channel of the Segami River mouth is double sectional and has a nearly horizontal apron. Photograph 2 shows the river viewed upstream from Nagisa Bridge. Waves are seen running up the river, and the wave height at this site were estimated to be about 0.6m, which was inferred from wet part of the left bank of revetment. In Photograph 3, situations of waves propagating through the river channel are shown with the box culvert in the distance. The height of waves at this point is about 1.0m, and the wave length between the two wave crests is estimated to be about 15.4m. Photograph 4 shows overflowing water at the point where the river is transformed into the box culvert near Kujihama Station. Water is seen flowing over the crown of the revetment down to the surrounding areas at a lower elevation.

Photograph 2 View from the Lowest Reach toward Upstream of the River



Photograph 3 Waves Running-Up the River Channel



Photograph 4 State of Inundation at the Box Culvert

PROPAGATION OF WAVE ENERGY AND MECHANISM OF INUNDATION

According to the results of the data analysis, major factors affecting outbreaks of inundation are, in order of decreasing period: ① the seasonal change of sea levels (Figure 4), ② sea level rises due to low pressure and wind-drift effects due to typhoons (Figure 3), ③ sea level fluctuation periods from several to 20 min as a result of secondary undulation of tides (Figure 5), and ④ swells penetrating into the river channel through the port. Secondary undulation (resonance) can also occur in a narrow channel, where periods are calculated to be about 7min and 2.5min. Among the four factors cited above, practical countermeasures may be taken against swells and secondary undulations with relatively short periods, both of which are considered the causes of inundation. In this section, therefore, we discuss the processes of propagation and the transformation of waves in the port, wave amplification within the river channel, and mechanisms of inundation.

Propagation of Swells

Swells penetrating into Hitachi Port pass through the anchorage, enter the river mouth and run up through the channel toward the uppermost end (Fig.6).

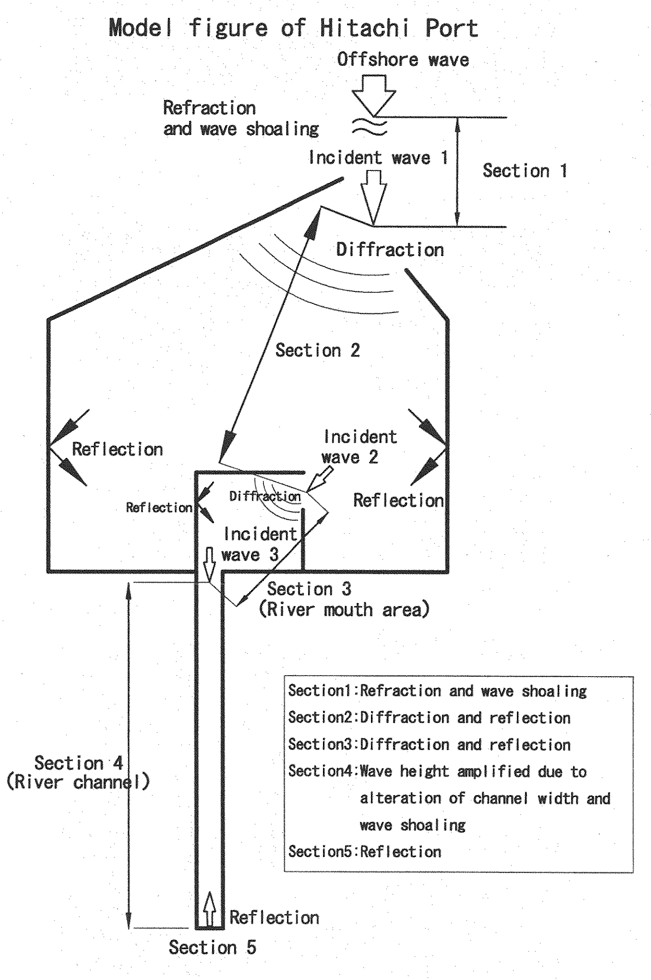



Figure 6 Penetration, Propagation and Transformation of Swells Offshore wave

Wave transformation in these processes is summarized as follows:

① From Offshore to the River Mouth

From offshore to the mouth of Hitachi Port, waves undergo refraction and wave shoaling under the influence of sea bed topography. Incident waves are diffracted by the breakwaters at the port entrance, thereby diminishing the wave height. Diffracted waves are reflected by breakwaters in the port. The diffracted and reflected waves overlap, and enter the anchorage in the innermost part of the port, where diffraction and reflection occur again. The composite waves of these penetrate into the river mouth.

② In the River Channel

Incident waves entering the river mouth run up through the channel. Change of wave height due to alteration of width and depth of the channel is governed by Green's law (2). In the Segami River, where the river channel becomes narrower and shallower toward upstream, wave height is amplified and reaches 1.3 to 1.5 times higher than at the river mouth according to Green's law.

The equation of Green's law is expressed as follows:

$$\frac{H_0}{H_i}=\left(\frac{B_i}{B_0}\right)^{\frac{1}{2}}\left(\frac{h_i}{h_0}\right)^{\frac{1}{4}} \tag{1}$$

were $H_i$ = height of incidence wave; $H_0$ = wave height of request point; $h_i$ = the depth of $H_i$ wave point; $h_0$ = the depth of $H_0$ wave point; $B_i$ = the channel width of $H_i$ wave point; $B_0$ = the channel width of $H_0$ wave point.

③ At the Uppermost End of Channel

The uppermost end of the channel is formed into a box culvert. As its cross sectional area is comparatively small for run-up waves, reflection occurs at this point.

Transformation of Swells between the Port and River Mouths

By means of wave transformation models, we calculated the propagation of waves from the port through the anchorage to the river channel. Procedures for performing the calculation are as follows:

① Because there are no observation data of waves in the Hitachi Port, wave height frequency obtained from the observation data at Hitachi-Naka Port was converted into wave height frequency at the front of Hitachi Port by means of wave energy balance equations.

② By using Takayama's model (3), wave height distribution in Hitachi Port was calculated, and the frequency ratio of wave heights entering the anchorage was estimated. Based on these findings, the wave condition that was used for the wave transformation calculation inside the anchorage was decided.

③ By means of wave transformation calculation in the anchorage using the linear long-wave model (4), wave height distribution within the anchorage was obtained.

The basic equations of the linear long-wave model are expressed as follows:

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{2}$$

$$\frac{\partial M}{\partial t}+gh\frac{\partial \eta}{\partial x}=0 \tag{3}$$

$$\frac{\partial N}{\partial t}+gh\frac{\partial \eta}{\partial y}=0 \tag{4}$$

$$M=h\bar{u} \quad ; \quad N=h\bar{v} \qquad (5);\ (6)$$

where $\eta$ = level of water surface; M, N = flow rate along x, y axis; h = water depth; g = acceleration due to gravity; $\bar{u},\bar{v}$ = mean velocity along x, y axis.

To understand more clearly the nature of wave transformation in front of Hitachi Port, we employed a numerical simulation of the wave energy balance equations for irregular waves by Karlsson (5). Under calculation conditions shown in Table 1, waves at Hitachi-Naka Port were converted to waves at Hitachi Port, and the wave height conversion coefficient was determined for each wave height and direction. The results are summarized in Table 2. By utilizing the simulation results, wave height at the port mouth of 97.5%-occurrence, which corresponds to the critical wave height for cargo handling of the port, was calculated to be 2.2m. This serves as the wave height condition for considering countermeasure works.

Wave amplification within the port was separately examined in two sections. For the section from the port entrance to the anchorage front (Refer to Figure 7), we employed the Takayama's method and calculated the distribution of wave height ratio for the direction of 97.4°, that is the representative energy concentration direction of incident waves, and for each combination of wave height and period given in Table 1. Findings are shown in Table 3, where the average wave height ratio at 4 points in front of the anchorage (Refer to Figure 7) is given. For three wave periods of less than 4s, 4s to 11s, and over 11s, inter- or extrapolated wave height ratio was multiplied with wave height at the port entrance, to obtain wave height frequency at the anchorage front. Resultant 97.5%-occurrence wave height at the anchorage front was 0.56m. This provides evidence that relatively frequent invasions of waves about 0.5m high can occur at this point.

In the section from the anchorage front to the river mouth, we examined transformation of incident waves of about 0.5m height by means of the linear long-wave model. As amplification of waves was expected in accordance with each period, 5 cases of wave period ranging from 6s to 14s, at interval of 2s, were calculated. Table 4 shows the results of the calculation, from which a greater amplification is observed for waves with the longer period from 12s to 14s. Wave height of the river mouth at 12s was biggest with 0.5 meters. Since the period of about 12s is equal to the natural period of the anchorage, swells with this period possibly resonate and enter the river channel without being damped, as is shown in Figure 7.

Table 1 Conditions for Wave Transformation Calculations

| Items | Values |
|---|---|
| Wave period (s) | 4.0, 7.0, 11.0 |
| Wave hight (m) | 0.5, 1.0, 4.0 |
| S max | 10, 10, 10 |
| Calculated area(Km×Km) | 97.5 × 67.0 |
| Mesh interval(m) | 500 |
| Number of meshes | 195 × 134 |
| Number of period divisions | 5 |
| Number of direction division | 36 |

Table 2 Results of Wave Transformation Calculations

| Rank of periods(s) | ~4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0~ |
|---|---|---|---|---|---|---|---|---|
| Conversion coefficient | 0.95 | 0.94 | 0.93 | 0.92 | 0.93 | 0.94 | 0.95 | 0.96 |

| Wave directions | NNW | N | NNE | NE | ENE | E | ESE | SE | SSE | S | SSW |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction departure | 38 | 32 | 25 | 18 | 10 | 3 | 0 | −4 | −6 | −8 | −10 |
| Conversion cofficient | 0.72 | 0.77 | 0.82 | 0.87 | 0.91 | 0.95 | 0.96 | 0.97 | 0.98 | 0.99 | 0.99 |

Table 3 Ratio of Incident Wave Height at Anchorage Front to Port Mouth

| Wave conditions | | | Height ratio at Anchorage front to Port Mouth |
|---|---|---|---|
| Height(m) | Period(s) | Direction(°) | |
| 0.5 | 4.0 | 97.4 | 0.27 |
| 1.0 | 7.0 | 97.4 | 0.24 |
| 4.0 | 11.0 | 97.4 | 0.25 |

Table 4 Wave Height in Anchorage Calculated for Different Period of Waves at Anchorage Front

| Wave conditions | | | Height in anchorage (m) | |
|---|---|---|---|---|
| Height (m) | Period (s) | Direction (°) | In front of river mouth | Maximum |
| 0.5 | 6.0 | 135 | 0.15 | 0.2 |
| 0.5 | 8.0 | 135 | 0.2 | 0.5 |
| 0.5 | 10.0 | 135 | 0.15 | 0.2 |
| 0.5 | 12.0 | 135 | 0.5 | 0.7 |
| 0.5 | 14.0 | 135 | 0.45 | 0.7 |

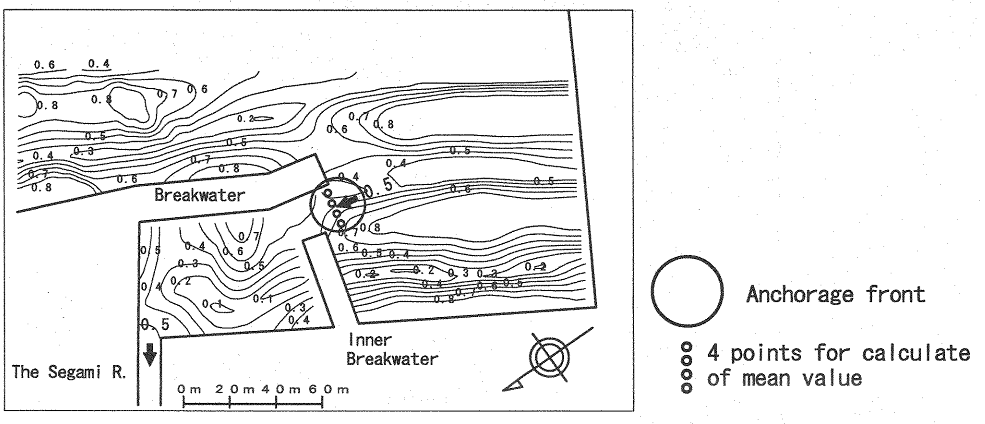



Figure 7 Example of Wave Height Distribution in Anchorage (m), Incident Wave of 0.5m height and of 12s-Period

Resonance and Transformation of Long-Period Waves in Hitachi Port

The secondary undulation detected in the tidal observation record of Hitachi Port is a result of resonance and transformation of long-period waves which enter the port. These long-period waves may propagate through the anchorage and into the river channel, causing inundation. We examined the resonance of these waves in the anchorage front by means of the linear long-wave model. Since no observation data of long-period waves at the port mouth are available, we assumed 10% of swell height (0.2m) and calculated the number of resonance of incident waves entering the port in the same direction as the swells, for 7 periods ranging from 60s to 300s. Results are shown in Table 5. Figure 8 illustrates the result for a 120s period for which high amplification was recognized. It can be seen that waves 0.2m high and of 120s period are amplified to about 0.6m high, which entered the river channel in the worst case.

Table 5. Change of Wave Height in the Port Due to Transformation of Long-Period Wave

| Wave conditions | | | Height in port | |
|---|---|---|---|---|
| Height(m) | Period(s) | Direction(°) | At Anchorage front(m) | Maximum(m) |
| 0.2 | 60 | 0 | 0.4 | 1.0 |
| 0.2 | 90 | 0 | 0.3 | 8.0 |
| 0.2 | 120 | 0 | 0.6 | 1.0 |
| 0.2 | 150 | 0 | 0.2 | 0.4 |
| 0.2 | 180 | 0 | 0.2 | 0.6 |
| 0.2 | 240 | 0 | 0.4 | 1.2 |
| 0.2 | 300 | 0 | 0.2 | 1.0 |

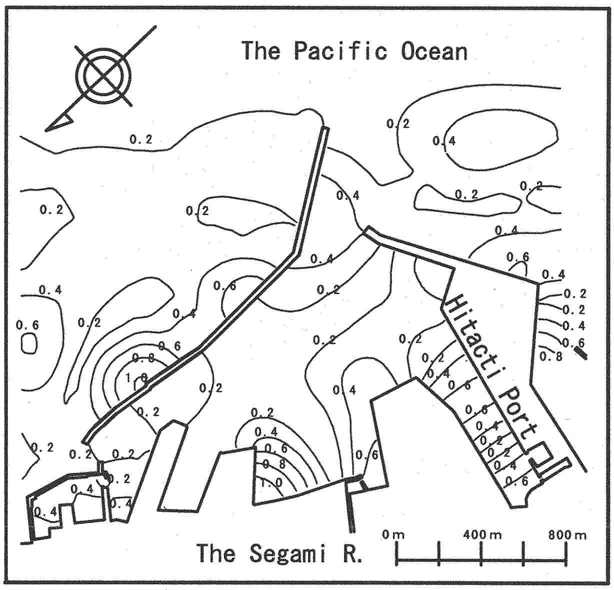



Figure 8 Transformation of Long-Period Waves Due to Resonance, Incident Waves of 0.2m High and of 120s-Period

Wave Amplification in the River Channel

Swells and long-period waves which reach the river mouth undergo further transformations while running-up the channel to the box culvert. To estimate the wave height that varied in the river channel, the transformation of swells (ordinary waves) was calculated both by Green's law and the linear long-wave model. The liner long-wave model was also used for examining long-period waves.

From the description regarding photographs No.2 to 4, the height of swells at the river mouth and near the box culvert and wave amplification ratio were estimated. These estimations were compared with the findings of the calculation based on Green's law and of the numerical model simulation, as shown in Table 6. In the simulation, 0.56m of incident swell height was used since the design wave height was excessively high. We had examined suitability of using either the critical wave height for cargo handling (less than 0.5m in Hitachi Port) or the wave height which secures calmness for mooring of ships in 97.5% of the days of a year (0.56m), and adopted the larger value. The calculations with Green's law were conducted for cases of no reflection and of perfect reflection, but in the numerical model simulation, calculations were made only for the cases of perfect reflection. The calculations with Green's law yielded a wave height 1.3m for case of no reflection and 2.6m for case of perfect reflection, and numerical model simulation yielded a wave height 2.59m for case of perfect reflection.

As seen in Table 6, although wave heights at the river mouth and at the box culvert which was employed in the numerical simulation were somewhat different from those estimated from the photographs, the wave amplification ratio coincided well with the value obtained by Green's law. The amplification ratio estimated from the photograph was intermediate between the cases of no reflection and of perfect reflection of Green's law method. This finding indicates that a part of waves inundates and a part of it is reflected, as can be seen in Photograph 4. From these results, it can be seen that the model can reproduce accurately the modification of swells in the river channel, and reveals theoretical values in a reasonably good agreement with the estimated values. These findings provide evidence that the numerical simulation method can be used to examine the effectiveness of countermeasures against inundation.

Transformation of long-period waves of 120s, which had resulted from resonance in Hitachi Port, was examined also by means of the numerical simulation. It was found that these waves amplified about 1.7 times in the river channel up to the box culvert. This reveals that the resonate period of Segami River channel and of Hitachi Port are similar values. And this is a cause of the water level increase in the Segami River channel. Since long-period waves are much more difficult to control than swells, their effects on inundation are considered to be very important.

Table 6 Comparison of Results Calculated by Green's Law and by Numerical Simulation

| Items | | Photograph 1 (River mouth) $H_1$ | Photograph 3 (Box culvert) $H_2$ | Amplification ratio of wave height $H_2/H_1$ | Remarks |
|---|---|---|---|---|---|
| Value estimated from photographs | | 0.5m | 1.1m | 2.2 | Value by *in situ* measurement based on photographs |
| Result of calculation | Green's law | | | Reflection neglected | River Widths and depths below M.S.L. |
| | | | | 1.3 | $h_1$=4.9m |
| | | | | | $h_2$=3.3m |
| | | | | Complete reflection | $B_1$=6.2m |
| | | | | 2.6 | $B_2$=3.5m |
| | Numerical simulation | 0.56m | 1.45m | 2.59 | Complete reflection assumed |

$h_1$ : Depth of River mouth., $h_2$ : Depth in front of box culvert
$B_1$ : Width of River mouth, $B_2$ : Width in front of box culvert

## Mechanism of Inundation

In short, there are two main factors causing inundation of the Segami River: the configuration of the river channel and the low elevation of the land it flows through. Firstly, the river mouth with depth of -4.29m below M.S.L. and widths of 7m facilitates penetration of waves from the sea, and the gentle slope of 1/900 allows penetrating waves to run up without being damped. The narrower river width upstream causes amplified wave height. At the uppermost end, the open channel is transformed into the box culvert, where reflected waves overlap running-up waves, resulting in further amplification of wave height. Secondly, land elevation near the Kujihama railway station, where the open channel ends in the box culvert, is as low as 1.1m to 1.3m above M.S.L., facilitating accumulation of rain water in this area. The crown of the revetment of the river is almost as high as the surrounding land, which also contributes to inundation.

In addition to these main factors, inundations can be triggered by the seasonal variation of tide level, rises of sea level due to meteorological tide, and invasions of long-period waves and swells. Mean tidal level is at the highest in autumn when almost all of the inundation damages occur, about 0.1m above the yearly mean tidal level. The meteorological tide due to low pressure raises the sea level sometimes over 0.2m, and when combined with the autumnal high tide, can result in a long duration of an elevated sea level over which waves propagate. But high water levels due to the seasonal and meteorological reasons are not high enough to cause inundation. Under these conditions, part of waves of certain periods, which produce the secondary undulations in Hitachi Port and consequent in a rise of wave height at the anchorage front, should always reach the river mouth. The undulation further resonates in the river and raises the water level in front of the box culvert.

According to the tidal observation records, most of the secondary undulations occur when a typhoon approached. The shape of Hitachi Port causes an intense resonance with waves of 120s-period, so that wave height of 0.2m at the port entrance can increase three times at the anchorage front. The long-period waves of 120s are further amplified during the course of the channel, creating waves 1.7 times higher than at the river mouth.

Swells, with the short period of waves that trigger inundation, propagate overlapping long-period waves and raise water levels in front of the box culvert complying with Green's law. The amplification ratio of a wave height of 12s period is about 2.5 at the river mouth.

Inundation is thought to occur when all or some of these tendencies coincide.

## DISCUSSIONS OF COUNTERMEASURES AGAINST INUNDATION

We examined 5 categorical methods for preventing inundation of the river by: ① damping of waves entering into the river channel, ② damping the waves which have penetrated into the channel, ③ blocking the penetration itself of waves into the channel, ④ intercepting the connection between the sea and the river channel so as to diminish the effects of the tidal variation, and ⑤ preventing overflow of rising water in the river channel by means of revetment structures.

Figure 9 illustrates the plans of the countermeasures related to the methods from ① to ④ above, in which construction works are to be done in and around the anchorage: an additional inner breakwater, elongation of the present inner breakwater, a man-made island, elongation of the present breakwater, a training jetty, a reduction pond, and a storm surge gate equipped with pump. It should be noted that the shape of reduction pond is determined by the shape of land available. The efficiency of wave damping for each of the plans that was given by comparison of wave height in front of box culvert is summarized in Table 7. The most effective one for swells is the construction of a new inner breakwater (Plan 1), which can damp the wave height to 42% of the present status. Construction of a reduction pond (Plan 6) is the most effective for long-period waves, with a 9% damping. The reduction pond is also effective against swells and long-period waves combined. No single measure, however, can lower the water level below the revetment crown height at the box culvert, 1.37m above M.S.L. Therefore, we examined the effectiveness of combinations of the new inner breakwater, the reduction pond and other measures, and found that the most effective plan is the combination of the reduction pond and the new inner breakwater, which will decrease the height of swells by 90% and the long-period wave height by 10% or more.

On the other hand, the measures to prevent waves from entering the river mouth can also hinder the smooth drainage of flood flow, causing a contradictory situation for the prevention of inundation. In view of this, we examined flood flow in cases of these measures undertaken, by means of a horizontal two-dimensional flow model calculation. As shown in Table 8, construction of any structure in the port results in the rise of the water level to about ten centimeters at the river mouth. It is therefore difficult to adopt measures other than construction of the reduction pond, if the design high-water level can not be altered. Even in the case of the reduction pond construction, in which an extensive widening of the river channel cross section is made, the water level will inevitably rise to a degree. But as the elevation of the land where the pond is to be constructed is high enough to rule out the possibility of inundation there, and the rising water level rapidly diminishes up- and downstream of the pond, we will not calculate the water level rise for this case.

The erection of a levee is generally considered to be a measure to prevent inundation due to water level rises in river channels. However, the raising of the revetment crown near Kujihama Station, where the land elevation is lower than the crown, is likely to lead to backward flows from the river through the sewage drainage system, and is excluded from the proposal of possible countermeasures in this study.

In the basin of the Segami River, it takes only 15minutes for flooding to occur after rainfall. A storm surge gate may rather result in greater inundation damages when a rapid drainage of flood flow within this short time after rainfall cannot be performed.

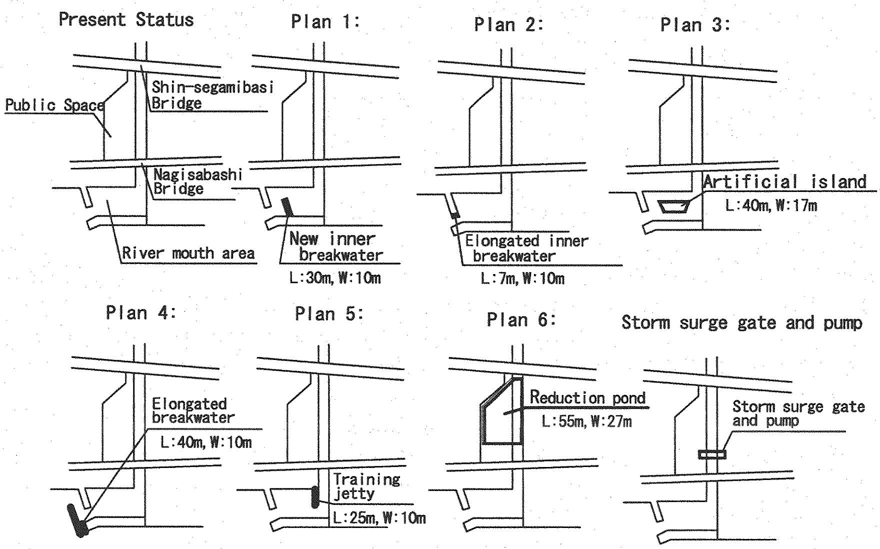



Figure 9 Plans of Countermeasure Works against Inundation

Table 7 Effectiveness of Measures of Wave Damping Works

| Countermeasures | Wave height (m) | | | Rise of water level (m) (1/2 wave height) | | |
|---|---|---|---|---|---|---|
| | Long-period wave | Swells | Combined | Long-period wave | Swells | Combined |
| Present status | 0.82 | 1.45 | 2.27 | 0.41 | 0.73 | 1.14 |
| Plan 1. New inner breakwater | 0.83 | 0.61 | 1.44 | 0.42 | 0.31 | 0.73 |
| Plan 2. Elongated inner breakwater | 0.88 | 1.39 | 2.27 | 0.44 | 0.70 | 1.14 |
| Plan 3. Artificial island | 0.75 | 1.46 | 2.21 | 0.38 | 0.73 | 1.11 |
| Plan 4. Elongated breakwater | 0.88 | 0.87 | 1.75 | 0.44 | 0.44 | 0.88 |
| Plan 5. Training jetty | 0.75 | 1.49 | 2.24 | 0.38 | 0.75 | 1.13 |
| Plan 6. Reduction pond | 0.66 | 0.97 | 1.63 | 0.33 | 0.49 | 0.82 |

Table 8 Change of Water Level at River Mouth for Countermeasure Works

| Countermeasures | Change of water level at river mouth (m) |
|---|---|
| Present status (standard) | 0 |
| Plan 1. New inner breakwater | 0.06 |
| Plan 2. Elongated inner breakwater | 0.48 |
| Plan 3. Artificial island | 0.08 |
| Plan 4. Elongated breakwater | 0.08 |
| Plan 5. Training jetty | 0.18 |

## CONCLUSION

We have demonstrated by this research that the plural factors affect the mechanism of wave running-up and inundation. The configuration of the river channel and the low elevation of the land are basic factors causing inundation. Form and geographic factors of the river channel are the unique characteristic about the Segami River. The narrower river width upstream and shallow water upstream are remote causes of inundation. Generally physical phenomena overlap these factors and inundation occurs. The physical factors around Segami River play a role in causing inundation. The factors include the seasonal changes of mean sea level, the rise of the sea level due to air pressure decline, the resonance of long-period wave in the port and the amplification of wave height.

We also propose that the construction of an additional inner breakwater, combined with a reduction pond, is the most practical countermeasure against inundation of the Segami River, which enable an effective damping of waves and has less adverse effects on drainage of flood flow. As the reduction pond is to be situated adjacent to the greenery park of Hitachi Port, it can be expected to serve as an area for relaxation where citizens enjoy waterside pastime. It must be noted that raise of the revetment might be needed in some places where the ground elevation could be slightly less than necessary although the chosen countermeasure was taken.

## REFERENCES


1. Uda, T. and K. Noguchi : Wave run-up damages at a small river mouth and its countermeasures -An example of the Okajima River mouth in Kyoto Prefecture-, Civil Engineering Journal, Vol.35, No.3, pp.60-65, 1993. (in Japanese)
2. Unoki, S : Ocean physics of the coast, Tokai University Press, 1993. (in Japanese)
3. Takayama, T. : Wave diffraction and wave height distribution inside a harbor, Technical Note of the Port and Harbour Research Institute, No.367, pp.1-40, 1986. (in Japanese)
4. Takayama, T., T. Hiraishi: Numerical calculation and field observation study for characteristics of harbor oscillation, Note of the Port and Harbour Research Institute. No.636, 1988. (in Japanese)
5. Karlson, T : Refraction of continuous ocean wave spectra, Proc. ASCE, Vol.195, No.WW4, pp.437-448, 1969.

## APPENDIX - NOTATION

The following symbols are used in this paper:

| | |
|---|---|
| $B_i$ | = the channel width of $H_i$ wave point; |
| $B_0$ | = the channel width of $H_0$ wave point. |
| g | = acceleration due to gravity; |
| h | = water depth; |
| $h_i$ | = the depth of $H_i$ wave point; |
| $h_0$ | = the depth of $H_0$ wave point; |
| $H_i$ | = height of incidence wave; |
| $H_0$ | = wave height of request point; |
| M, N | = flow rate along x, y axis; |
| $\overline{u}, \overline{v}$ | = mean velocity along x, y axis; and |
| $\eta$ | = level of water surface. |

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